ESD-TR-80-20

ADA085656

See 1473

(12)

LEVEL II

Technical Note	1980-17
Plasma X-ray Sources for Lithography	N. P. Economou 12 March 1980

Prepared for the Defense Advanced Research Projects Agency under Electronic Systems Division Contract F19628-80-C-0002 by

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LEXINGTON, MASSACHUSETTS

The work reported in this document was performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology. This work was sponsored by the Defense Advanced Research Projects Agency under Air Force Contract F19628-80-C-0002 (ARPA Order 3777).

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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PLASMA X-RAY SOURCES FOR LITHOGRAPHY

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Group 87

TECHNICAL NOTE 1980-17

12 MARCH 1980

LEXINGTON MASSACHUSETTS

ABSTRACT

The X-ray source is an important part of any X-ray lithographic system since its characteristics affect ultimate resolution and throughput. High temperature plasmas can be intense X-ray emitters and may be suitable for lithography. This report defines some general considerations which are helpful in evaluating various plasma sources. In addition, a brief analysis is given of three devices, or systems, used to produce such plasmas: the electron beam-sliding spark, the dense plasma focus and the laser produced plasma.

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I. Introduction

Pulsed, high temperature plasmas offer a possible alternative to conventional electron bombardment X-ray sources for lithography.[1] The main drawback of conventional sources is their low conversion efficiency from electrical input to X-rays ($\sim 10^{-4}$).[2] In practice this limits the brightness of the source, resulting in long exposure times for standard X-ray resists. Plasmas have been shown to be intense, efficient (as much as 50% of input converted to X-rays[3]) sources in the soft X-ray region and may be suitable for lithography. An ideal source would be less than 1 mm in size with an output spectrum peaked near $\lambda = 10$ Å and an average output power of at least 10 W (2 minute exposure of PMMA at 10 cm distance). It has been suggested[4] that, using a large plasma device, resist exposure might be achieved with a single pulsed event of a few nanoseconds duration. For PMMA the X-ray power density impinging on the mask and substrate would then be 10^8-10^9 W/cm^2. This could cause severe damage to the mask or cause the resist to be ablated from the substrate surface. A safer approach would be to use a smaller device having moderate peak output power but capable of a high repetition rate.

Devices used to produce hot laboratory plasmas fall into three broad categories:

1. Electrical Discharge (e.g., exploding wires, dense plasma focus, sliding spark, etc.)
2. Beam-Target (usually electron or laser beam with solid targets)
3. Combinations of (1) and (2).

The electron beam-sliding spark,[5] under study at IBM and here at Lincoln Laboratory, falls into category (3). All of these devices are simple in concept, however the details of their behavior and the effects of various parameters on X-ray production are often poorly understood. This is due partly to the experimental difficulty of properly diagnosing and characterizing the plasma. In addition, accurate theoretical models are extremely difficult to develop due to the large number of physical processes involved and the non-equilibrium nature of pulsed events. These problems notwithstanding, it is often possible to put limits on the performance of a given device by using available experimental results and applying some simple physical arguments to scale to larger or smaller input energies. A useful set of scaling considerations will be outlined in Section II. The electron beam-sliding spark and two other possible plasma X-ray sources will be discussed in Sections III and IV.

II. General Considerations

When considering plasma X-ray emission as a lithographic source, it is the blackbody portion of the spectrum which is of most interest. Although strong line emission has been observed in some experiments,[6] a single line or group of lines usually contains only a small fraction of the total radiated energy ($\sim 10^{-4}$ or less). Blackbody emission accounts for the majority of the energy and occurs over a narrow enough band so that a reasonable fraction of it (10% or more) could be used for exposing resist through an absorber pattern. In the following discussion, the plasma will be treated as a true blackbody radiator. This implies thermodynamic equilibrium which clearly cannot be the

case over the whole course of a pulsed event. However, the time-integrated spectra of dense laboratory plasmas are reasonable approximations to blackbody curves and will be treated as such below.

A blackbody radiator has a spectrum which is completely determined by a single parameter, the temperature, T. The peak of the distribution occurs at a wavelength*

$$\frac{hc}{\lambda_{peak}} = 5\ kT \tag{1}$$

and the total radiated power from the surface is given by

$$I_{TOT} = 5.67 \times 10^{-12}\ T^4\ W/cm^2 \tag{2}$$

for T in degrees Kelvin. As will be seen in Section III, this rapid increase in the radiated power with temperature is the main obstacle to scaling laboratory devices to produce shorter wavelengths.

Of the many device and plasma characteristics affecting soft X-ray production, there are three which, when taken together, give a good indication of the performance limits of a system. These are:

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*This relation holds when the expression for the radiation intensity per unit wavelength is used. If the intensity per unit frequency (energy) interval is used then the relation becomes:

$$h\upsilon_{peak} = \frac{hc}{\lambda_{peak}} = 2.8\ kT$$

1. input power density
2. plasma disassembly time
3. plasma electron density.

The first of these, the input power density, is seen to be important from a simple energy balance argument. Assuming that a plasma has been created which behaves as a blackbody, then it will lose energy from its surface by radiation at a rate given by equation (2). If the temperature of the plasma is to be maintained, at least the same amount of power must be provided from the external driving source. For example, a blackbody at a temperature of $3 \times 10^6\,^\circ$K (kT $\approx$ 240 eV) has its peak at a wavelength $\lambda \approx 10$ Å and radiates 4.6×10^{14} W/cm^2 from its surface. This loss must be balanced by putting energy back in at the same rate and into the same size volume. For a laser heated plasma this would require a pulse of peak power 4×10^{10} W (40 J in 1 ns) focused onto a 100 μm diameter spot. For an electron beam heated plasma, a 50 kV, 3×10^5 A beam would be required for the same spot size (current density = 4×10^9 A/cm^2). This type of analysis ignores other energy loss mechanisms and thus gives a lower limit for the input.

The second parameter, the plasma disassembly time, is the time it takes for the plasma to expand out of the volume being supplied with external energy. This flux of particles is a loss mechanism which cools the plasma and reduces the radiated power. The expansion time is determined primarily by the ion acoustic speed, given by[7]

$$v_i \approx \left(\frac{2Z\,kT}{M_i} \right)^{1/2}$$

where Z is the ionization state of the ion, k the Boltzmann constant and M_i the mass of the ion. For a plasma of He-like carbon at 240 eV this velocity is 1.6×10^7 cm/sec (160 μm/ns). Ideally, a pulsed event should last no longer than a time d/v_i where d is the initial size of the plasma. For typical devices d is usually between 0.1 and 1 mm giving times in the range of 0.6 to 6 ns for the example above. Events lasting longer than the disassembly time require an increase in the input power density to compensate for the energy carried out by the particles. In addition, the less dense plasma formed by the expanding cloud of particles may interfere with the coupling of input energy into the desired source volume.

The third parameter is the electron density of the plasma. The radiation processes of importance for X-ray emission are bremsstrahlung, recombination and line radiation, which are all proportional to the product of electron density, n_e, and ion density n_i. Due to the relative ease of stripping outer electrons from ions and the relative difficulty of stripping the last two electrons, n_i is, to a reasonable approximation, proportional to n_e. Therefore, radiation processes are roughly proportional to n_e^2. In addition to increasing the radiation efficiency, a high electron density makes the plasma optically thick to its own radiation and improves the coupling of the plasma particles to each other through collisions. Both of these effects make the plasma a better approximation to a true blackbody radiator. In general, as high an electron density as possible is desirable. A practical lower limit would be $n_e \sim 10^{19}/\text{cm}^3$. Densities of $10^{21}/\text{cm}^3$ or higher are ideal.

From the above considerations one can see roughly what is necessary for a successful plasma soft X-ray source:

(a) input power density $\gtrsim 10^{14}$ W/cm^2

(b) plasma size $\sim$ 100 μm

(c) event time $\sim$ 1 ns

(d) electron density $\gtrsim 10^{21}/\text{cm}^3$.

III. The Electron Beam-Sliding Spark

The electron beam-sliding spark[5] is a device which utilizes an energetic electron beam to heat a target plasma formed by a high voltage arc through a polyethylene channel.[8] This device has been operated successfully and been most carefully studied at IBM.

The output spectrum of the IBM device has a blackbody character but with a fairly intense carbon line spectrum also apparent. This probably is due to the rather low electron density ($\sim 10^{19}/\text{cm}^3$) achieved. Most of the energy is in the blackbody part of the spectrum which peaks around λ = 180 Å or $T = 1.6 \times 10^5$ °K with a total radiated energy of approximately 0.4 J/pulse. This amount of soft X-ray output is consistent with the source area of 10^{-3}cm^2 and event time of 100 ns, both measured independently of the X-ray energy. The input energy was 40 J so that about 1% of the input was converted to X-rays.

Assuming that the source size and event length remain the same, it is possible to estimate how large a device would be necessary to shift the blackbody emission to shorter wavelengths. With peak output at λ = 10 Å or $T = 3 \times 10^6$ °K, the electron beam-sliding spark would radiate 4.6×10^4 J during each 100 ns pulse. If the conversion efficiency from electrical input

to X-ray emission remained the same, an input energy of 4.6×10^6 J would be required. A high speed capacitor bank of this size is too unwieldly to be considered seriously for lithography. In order for an electrical system of reasonable size ($\lesssim 10^4$ J) to be used, the following plasma characteristics would be needed:

(1) conversion efficiency to X-rays $\sim$ 10%,

(2) event length $\sim$ 10 ns,

(3) source area $\sim 10^{-4} cm^2$.

Each of these is an order of magnitude different than the present device. The first requirement is probably reasonable since experimental results on other types of devices show improved radiation efficiency with increased input energy and plasma temperature. The event length is determined by both the intrinsic rise time of the capacitor bank and the electrical characteristics of the plasma load. At present, the load inductance seems dominant, making improvement in this quarter questionable. The source area is determined by the dynamics of the plasma itself. At increased input energies (currents), self-generated magnetic fields would be stronger, increasing the tendency of the plasma to contract perpendicular to the current flow (Z-pinch configuration). Opposing this would be the particle pressure of the plasma which increases with temperature and number density. The net result of this is difficult to predict and other experimental conditions, such as channel diameter, could play an important role.

Here at Lincoln Laboratory, an upgraded 1600 J version of the electron beam-sliding spark is near completion. The performance of this device will answer many of the questions concerning scaling. Applying the simple analysis

used above and assuming the same efficiency, event time and source area as the IBM device, one would expect peak emission at λ = 50-100 Å with 10-20 J total X-ray output per pulse.

IV. Other Plasma X-ray Sources

There are many other ways to produce hot, dense plasmas each having relative strengths and weaknesses as an X-ray source. There are two, however, which seem more likely to satisfy the needs of lithography.

The first of these is the dense plasma focus or coaxial plasma focus developed by Mather[9] in the mid-1960's. Reference 10 gives an excellent review of its important characteristics. One advantage of the plasma focus is that a somewhat slower external circuit can be used (risetime $\sim 10^{-6}$ s) since the plasma is formed by a dynamical self-focusing in the discharge chamber. Event times are on the order of 10^{-7} s which is comparable to the electron beam-sliding spark. Large plasma focus devices with inputs of 10^5 J or more have produced intense line and continuum radiation, though quantitative results on X-ray yields are difficult to find. The real question here is whether smaller devices will also prove to be intense X-ray emitters. A series of experiments is now underway at the University of Houston on a plasma focus using 5-10 kJ input energy.[11] Initial results are somewhat uncertain but experiments to be performed in the near future should indicate the usefulness of this approach.

The second promising candidate is the laser-produced plasma, formed by irradiating a solid target with a focused, high intensity laser beam. This type of arrangement decouples the energy delivery system from the target,

making the system simpler to understand than discharge devices. Laser plasmas have the highest demonstrated conversion efficiency (50%)[3] of input energy (optical) to X-rays. They are also among the most thoroughly studied and best understood plasmas due to their possible use for nuclear fusion. Experiments to date have concentrated on CO_2 or Nd:glass laser systems operating at wavelengths of 10.6 μm and 1.06 μm respectively. While some experiments[4,12] have achieved X-ray outputs large enough to expose resists in a short time, the lasers needed to do this are too large, complicated and costly to be of interest for lithography.

One hopeful result is the large increase in conversion efficiency of input to X-rays obtained by using the shorter wavelength Nd:glass laser. This is thought to be the result of improved coupling of the laser energy to the plasma. The particle density of a laser produced plasma is a maximum at the target and decreases with distance from the surface. The laser beam propagates through the plasma until its frequency is equal to the plasma frequency:

$$\omega_{laser} = \frac{2\pi c}{\lambda_{laser}} = \omega_{plasma} \propto (n_e)^{1/2} \qquad (3)$$

At this point the energy will be absorbed or reflected. The electron density, n_e, where the coupling takes place is seen to increase as $1/\lambda^2$. The increase in n_e from $10^{19}/cm^3$ to $10^{21}/cm^3$ in going from 10.6 μm to 1.06 μm radiation increases the fractional absorption of laser energy and improves the collisional coupling of the laser heated electrons to the rest of the plasma. Preliminary experiments at Lawrence Livermore Laboratory, using a frequency

doubled Nd:glass laser ($\lambda = 5320$ Å), indicate that performance continues to improve at shorter wavelengths.

This trend suggests the use of excimer lasers, either KrF at $\lambda = 2490$ Å or ArF at $\lambda = 1930$ Å. In addition to the shorter wavelengths, these lasers have the advantage of being able to produce pulses at high repetition rates ($\sim$ 100/s), and thus high average powers, an important consideration for lithography. The improved coupling and increased electron density expected at UV wavelengths may allow efficient X-ray production with modest pulse energies of the order of a few Joules. The required input power density ($\sim 10^{14}$ W/cm^2) would have to be achieved by focusing to smaller spots. The disadvantage of this approach is that plasma disassembly losses will be important since pulsewidths of less than 5-10 ns are difficult to achieve with excimer lasers, while the ideal pulse duration would be 1 ns or less.

Due to the relatively recent development of UV excimer lasers, little work has been done on generating plasmas. It is not clear if the advantages of using UV wavelengths will offset the increased losses incurred by having longer pulses, and lead to efficient X-ray production. Computer simulations will be undertaken to investigate the effects of the various important parameters (e.g., pulse length, spot size, wavelength), however, good quantitative experimental results will be needed before the issue can be decided.

V. Conclusion

The requirements of X-ray lithography place severe demands on any plasma source. As shown above, producing plasmas of 3×10^6 °K temperature requires extremely high input power densities. Short event times and high particle densities are needed to insure efficient conversion of input energy to X-rays. Small plasma surface areas and short event times are both necessary if the total input energy is to be kept to a manageable level. Reliable performance at high average power outputs is also required. At the present time, none of the approaches discussed above is able to meet all these conditions at an acceptable cost. The three options which appear most promising are the electron beam-sliding spark, the dense plasma focus and the UV excimer laser plasma. Research is now in progress in all three areas but success may depend on new technological developments such as faster discharge devices or excimer lasers with shorter pulselengths.

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18 19

REPORT DOCUMENTATION PAGE

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BEFORE COMPLETING FORM

1. REPORT NUMBER: ESD-TR-80-20
2. GOVT ACCESSION NO.: AD-A083 656
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): 6 Plasma X-ray Sources for Lithography
5. TYPE OF REPORT & PERIOD COVERED: 9 Technical Note
6. PERFORMING ORG. REPORT NUMBER: Technical Note 1980-17
7. AUTHOR(s): 10 Nicholas P. Economou
8. CONTRACT OR GRANT NUMBER(s): 15 F19628-80-C-0002
9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Lincoln Laboratory, M.I.T.
P.O. Box 73
Lexington, MA 02173
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
ARPA Order 3777
Program Element No. 61101E
16 Project Nos. 0D10 & 0D30
11. CONTROLLING OFFICE NAME AND ADDRESS:
Defense Advanced Research Projects Agency
1400 Wilson Boulevard
Arlington, VA 22209
12. REPORT DATE: 11 12 March 1980
13. NUMBER OF PAGES: 20
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
Electronic Systems Division
Hanscom AFB
Bedford, MA 01731
12 18
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report):
14 TN-1980-17
Approved for public release; distribution unlimited.
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:
None
19. KEY WORDS (Continue on reverse side if necessary and identify by block number):
x-ray lithographic
dense plasma focus
electron beam-sliding spark
laser produced plasma
20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

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